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MEASURING THE SALINITY OF IRRIGATION WATERS AND OF SOIL SOLUTIONS WITH THE WHEATSTONE BRIDGE

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INTRODUCTION

The Wheatstone bridge has been in use many years for measuring the salinity of irrigation and drainage waters and of soil solutions. A portable type of this apparatus was developed in the Division of Soils (now a part of the Bureau of Chemistry and Soils) as early as 1896,[1] and subsequently modified and improved. A description of this portable bridge of the type extensively used in soil surveys was published in 1910.[2]

The portable bridge was designed primarily for testing the salinity of soils; and while the instrument could be used for measuring the salinity of such solutions as irrigation and drainage waters, it was not wholly satisfactory for such use, chiefly because the electrodes could not be platinized and consequently the resistance readings were not definite.

Meanwhile the use of electrical methods for measuring the concentrations of solutions has been greatly extended. New types of bridges have been constructed and numerous forms of electrode vessels have been devised. Furthermore, there have been changes made in the interpretation of results of the electrical determinations. Formerly in soil investigations the observed resistances were corrected for temperature by means of a conversion table and then expressed as percentages of salt to the dry weight of soil. Latterly the results are more often expressed in terms of specific electrical conductance (the reciprocal of the specific resistance in ohms) at a stated temperature.

[1] WHITNEY, M., and MEANS, T. H. AN ELECTRICAL METHOD OF DETERMINING THE SOLUBLE SALT CONTENT OF SOILS. U. S. Dept. Agr., Div. Soils, Bul. 8, 30 p., illus. 1897.

[2] DAVIS, R. O. E., and BRYAN, H. THE ELECTRICAL BRIDGE FOR THE DETERMINATION OF SOLUBLE SALTS IN SOILS. U. S. Dept. Agr. Div. Soils, Bul. 61, 36 p., illus. 1910. This bulletin is now out of print and is superseded by the following publication:

——— THE USE OF THE ELECTROLYTIC BRIDGE FOR DETERMINING SOLUBLE SALTS. U. S. Dept. Agr., Circ. 423, 14 p., illus. 1927.

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The purpose of this circular is to describe the apparatus and the methods now used in the Division of Western Irrigation Agriculture for the determination of the salinity of irrigation and drainage water and also of the salinity of the solution suspended in an irrigated soil. The equipment herein described is intended for use in a laboratory or office to which the samples are brought, rather than to be carried from place to place for field use.

APPARATUS

The essential elements of the equipment include a suitable source of alternating current, a Wheatstone bridge, a telephone receiver, a water bath, and two conductivity cells—one for water and another for soil. These are enumerated and described as follows:

(1) The source of alternating current is a microphone hummer that delivers the current at a constant frequency of 1,000 cycles, operated by a battery of four dry cells delivering 6 volts of direct current.

(2) The Wheatstone bridge is of the inclosed dial type with a rheostat of four decades (1+10+100+1000) and a dial control of the ratio arms. The ratio arms have seven multiplying values—0.001, 0.01, 0.1, 1, 10, 100, and 1,000. Thus the range of the bridge is from 0.001 ohm to 1,000,000 ohms.

(3) The telephone receiver is of the double type of 1,000 ohms resistance, with a headband.

(4) The water bath may be constructed to meet individual requirements. If results of high accuracy are desired the bath should be of large size, well insulated, and with temperature control within a range of 0.1° C. For less precise work temperature control is not essential, and the bath is used merely to insure that the samples to be tested and the reference solution are at the same temperature. Or if only water samples are to be tested and a duplex conductivity cell is used, a water bath is unnecessary.

(5) The conductivity cell used for water samples is either of the immersion or the pipette type. Both are of glass with platinum electrodes. The immersion cell has a cell factor of approximately 1.3 reciprocal cm and is well adapted for use with the more saline irrigation and drainage waters. It is used with a large test tube and requires about 60 cm^3 of sample. The pipette cell has a cell factor of approximately 0.3 reciprocal cm and is useful for waters of low salinity. The conductivity cell used for soil samples is a cylindrical cup of hard rubber, with a capacity of 50 cm^3. The electrodes are of brass with disks of platinum attached to the inner faces. It has a cell factor of approximately 1.2 reciprocal cm.

ASSEMBLY AND OPERATION

The microphone hummer is placed in a dust-tight box packed in cotton and set at some distance from the bridge to avoid its sound interference. The battery is attached to it in series, with a switch in the circuit inserted near the bridge. The leads from the microphone hummer to the bridge are of heavy insulated wire and are attached through the switch to the battery (Ba. or E.M.F.) binding posts of the bridge. The leads from the telephone receiver are attached to appropriate binding posts marked "Ga." or "Tel.," and the leads from the conductivity cell are attached to the binding posts marked "X." These leads from the conductivity cell should be of flexible wire and should be of equal length and resistance.

New conductivity cells should be cleaned and the electrodes platinized before using. Subsequently they should be cleaned and replatinized whenever the readings become erratic or indistinct or when

inspection shows that any of the platinum black has flaked off. The glass cells are cleaned with an acid solution containing 2 parts of HNO_3, 3 parts HCl, and 3 parts water cooled to room temperature. New cells are simply washed in this solution and rinsed several times in distilled water. In cleaning used electrodes, to remove the coating of platinum black, the cell is filled with the acid and electrolyzed with a weak current (one or two dry cells); the direction of the current is changed after each minute until the electrodes are clean and bright, and they are then rinsed with acid followed by distilled water. Care must be taken not to allow the acid solution to remain in contact with the electrodes longer than necessary, as the platinum is soluble in this acid, especially when it is warm. The soil cup, made of hard rubber, should not be cleaned with acid, but the platinum black may be removed from the electrode faces by rubbing with absorbent cotton soaked in ethyl alcohol or water.

The cleaned electrodes are platinized with a solution composed of 3 g of platinic chloride and 0.2 to 0.3 g of lead acetate in 100 cm^3 [3] of distilled water.[3] The conductivity cell is partly filled with this solution so that the electrodes are immersed. A direct current (from one or two dry cells) is connected to the two electrodes, the direction being changed after each minute until the electrodes are well covered with the black coating. The cell is then rinsed several times with distilled water. It should be kept filled with or immersed in water when not in use. The platinizing solution may be reused.

In making conductance determinations, whether of water or of soil, the conductivity cell is first filled with a standard or reference solution and the resistance is measured with the Wheatstone bridge. The cell is then filled with sample to be tested, and the resistance is again measured. It is essential that the temperature of the reference solution and of the sample shall be the same when the resistances are measured, hence the need of a water bath unless the duplex conductivity cell is used. For such a reference solution one may use any convenient salt such as NaCl or KCl, and a convenient concentration is 0.01 normal or 10 mg equivalents per liter. The specific electrical conductance, at 25° C., of 0.01 normal NaCl is 0.001186 reciprocal ohms,[4] or 118.6×10^{-5}, while that of KCl at the same concentration and temperature is 0.0014118, or 141.18×10^{-5}.

The relationships between resistance, R, cell factor C, and specific electrical conductance, K, are shown in the following equation, where K is known and R is observed:

$$RK=C \qquad (1)$$

Thus, if the reference solution were 0.01 normal (r 10) KCl, its temperature 25° C., and its observed resistance 935 ohms, by substituting values in the equation we would have $935 \times 0.00141118=1.32$ as the cell factor for the conductivity cell at 25°.

Thence, if the same conductivity cell were filled with a sample of unknown specific conductance, but at the same temperature, and

[3] Cm^3 and g are the abbreviations recently adopted by the Government Printing Office for cubic centimeter and gram.

[4] WASHBURN, E. W., and KLEMENC, A. ELECTRICAL CONDUCTIVITY OF AQUEOUS SOLUTIONS, part 1, CONDUCTIVITY OF NEUTRAL HALIDES, NITRATES, AND SULPHATES. *In* National Research Council, International Critical Tables of Numerical Data, Physics, Chemistry, and Technology. Vol. 6, p. 233. New York and London. 1929.

the observed resistance was 465, the specific conductance, K, of the sample would be derived from the equation:

$$\frac{C}{R}=K \qquad (2)$$

or by substituting values $1.32 \div 465 = 0.00284$, or 284×10^{-5} reciprocal ohms at 25° C.

Thus, by having available a reference solution of which the specific conductance at a certain temperature is known, one may observe the resistance of that solution at that temperature, from this resistance reading determine the cell factor of the conductivity cell, and then by measuring the resistance of an unknown sample at the same temperature determine the specific electrical conductance of the sample.

TEMPERATURE COMPENSATION

It can not be too strongly emphasized that the electrical resistance of a solution and reciprocally its electrical conductance is influenced by its temperature. The resistance varies inversely as the temperature. Consequently, the matter of temperature control or temperature compensation is of the highest importance in conductivity work. In a well-equipped laboratory, with a bath of water or oil where the temperature may be controlled, this source of error may be reduced to a low point. But many engineers and irrigation managers who desire to determine the salinity of irrigation or drainage waters can not afford to install apparatus for temperature control. Fortunately, it is possible to make fairly accurate conductance measurements without temperature control. This may be done by either of two methods: (1) The temperature of the solution may be taken at the time the resistance is measured, and the observed resistance may be corrected by the use of a reference table or correction factor. Such a reference table for correcting resistance readings to a basis of 60° F. has been published by the Division of Soils.[5] Observations as to the effect of temperature on the resistance of dilute solutions of mixed salts such as are found in irrigation and drainage waters show that a difference of temperature of 1° C. changes the resistance in the opposite direction by 2.25 per cent; in other words, the temperature coefficient is approximately 0.0225. (2) The sample and the reference solution may be brought to the same temperature, the resistance of each determined in the same conductivity cell, and the conductance of the sample be computed from the two resistance readings. Experience with both methods has shown that the second is not only simpler but also yields more accurate results.

The basic assumption involved in the use of the second method of temperature compensation here described is that the temperature coefficient of the reference solution is so nearly the same as that of the salt solutions found in irrigation and drainage waters as not to cause appreciable error. A careful and extensive series of comparisons has shown that this assumption is valid. The procedure for temperature compensation here recommended follows.

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[5] Davis, R. O. E., and Bryan, H. Op. cit. (See footnote 2.)

A stock supply of reference solution is prepared and its concentration and its specific electrical conductance is carefully tested. For example, a solution of KCl is used having a concentration of 0.01 normal and specific conductance, at 25° C., of 141×10^{-5}. Two aliquots of this reference solution are drawn into sample bottles or into test tubes for the immersion type of conductivity cell, and placed in a water bath. Similar aliquots are drawn from the samples of water to be tested and also placed in the water bath. When the samples and the reference solutions have reached temperature equilibrium the conductivity cell is rinsed in one of the reference solutions and then filled with the other. This practice of rinsing lessens the danger of contaminating the standard reference solution. The resistance of the reference solution is then determined. The conductivity cell is then rinsed in one aliquot of the water sample and filled with the second aliquot and the resistance is determined. In this case also the preliminary rinsing lessens the risk of contamination.

Let it be assumed that the specific conductance, K, of the reference solution is known to be 141×10^{-5} at 25° C., that its observed resistance, R_{st}, at the unknown temperature of observation is 945 ohms, and that the observed resistance R_x of the water sample at the same unknown temperature is 1,260 ohms. In order to derive the specific conductance of the water sample ($K\times10^5$ at 25° C.) the following computations are made:

$$K\ R_{st}=C \text{ or } 945\times0.00141=1.33, \text{ whence } \frac{C}{R}=K \text{ at } 25^\circ \text{ C.}$$

$$\text{or } 1.33\div1{,}260=0.00105=105\times10^{-5}.$$

Thus the specific conductance of the sample ($K\times10^5$ at 25° C.) is 105.

THE DUPLEX CONDUCTIVITY CELL

It has been shown under Temperature Compensation that if a reference solution and a water sample are in temperature equilibrium and the electrical resistance of each is determined, it is possible to compute the specific electrical conductance of the water sample, as at 25° C., even though the temperature is unknown. The procedure described involved the use of a water bath to insure that the reference solution and the sample should be at the same temperature when their resistances were determined, and it involved also the use of the same conductivity cell for the two resistance determinations. It is apparent that it would be possible to dispense with the water bath by using two similar conductivity cells so placed as to insure temperature equilibrium.

The duplex conductivity cell has been designed to be used when a suitable water bath is not available. It consists of two immersion conductivity cells, mounted side by side in a disk of hard rubber. This rubber disk is designed to fit into the top of a cylindrical fruit jar of 1 quart capacity. (Figs. 1 and 2.) One of the conductivity cells (the open one shown in fig. 1) has a small opening at the bottom and another at the top so that it will be filled with the water sample when placed in the jar. The other conductivity cell shown in Figure 1 is closed at the bottom and open at the top through a small tubulature which may be closed with a rubber stopper. The closed cell is filled with the reference solution.

The leads from both cells are attached to binding posts on the top of the hard-rubber disk. From these binding posts they are extended to a double-pole, double-throw switch by means of which either cell may be connected with the Wheatstone bridge. (Figs. 2 and 3.)

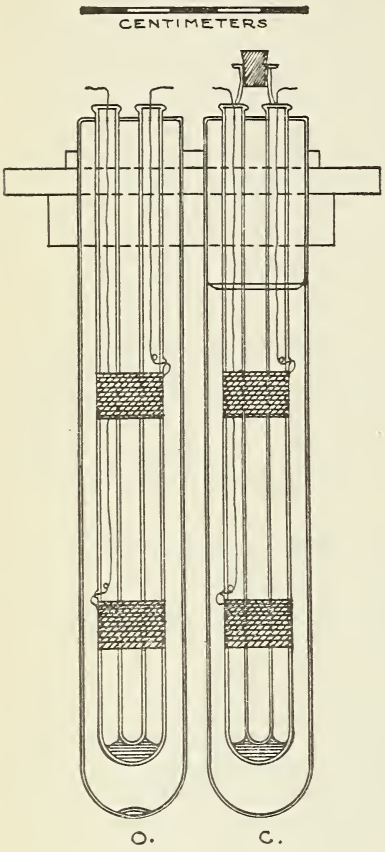

FIGURE 1.—Sectional view of duplex conductivity cell mounted in a disk of hard rubber; O, The open cell immersed in the unknown solution; C, the closed cell filled with a reference solution of known specific electrical conductance

For standardization the cells are cleaned and the electrodes are platinized. The closed cell is then filled with the reference solution, and the duplex cell is placed in a jar filled to the mark with the same reference solution. The contents of the jar are then brought to a temperature of 25° C., and the resistance of each cell is determined. From these resistance observations and the equation $R\ K=C$ the cell factor of each cell is computed. An example of the computations involved may be taken from the report of L. V. Wilcox, of this division, on a duplex cell, Gray Instrument Co. No. 7740. The reference solution used was of sodium chloride having a specific electrical conductance, K, of 0.001204 reciprocal ohms at 25°. The temperature of the jar's contents was adjusted to 25°. At this temperature the resistance of the closed cell, R_c, was 1,065 ohms and that of the open cell, R_o, was 1,085 ohms. The cell factors from the equation $RK=C$ were for the closed cell, C_c, 1.28 and for the open cell, C_o, 1.30. This completes the standardization.

The duplex cell was then transferred to another jar containing a water sample of which neither the temperature nor the conductance was known. After the lapse of time, to insure temperature equilibrium between the reference solution in the closed cell and the water sample, the resistances were determined to be, for the closed cell, R_c, 1,113 ohms and for the open cell, R_o, 905 ohms. Now since

$$\frac{R_o \text{ at } 25^\circ}{R_o \text{ at } X^\circ}=\frac{R_c \text{ at } 25^\circ}{R_c \text{ at } X^\circ}, \text{ or } \frac{R_o \text{ at } X^\circ \times R_c \text{ at } 25^\circ}{R_c \text{ at } X^\circ}=R_o \text{ at } 25^\circ$$

and $\frac{C_o \text{ at } 25^\circ}{R_o \text{ at } 25^\circ}=K$ at 25°, or the specific conductance expressed as reciprocal ohms.

By substituting values for symbols we have:

$$\frac{905 \times 1065}{1113}=865 \text{ and } \frac{1.30}{865}=0.00150, \text{ or } K \times 10^5 \text{ at } 25^\circ \text{ C.}=150.$$

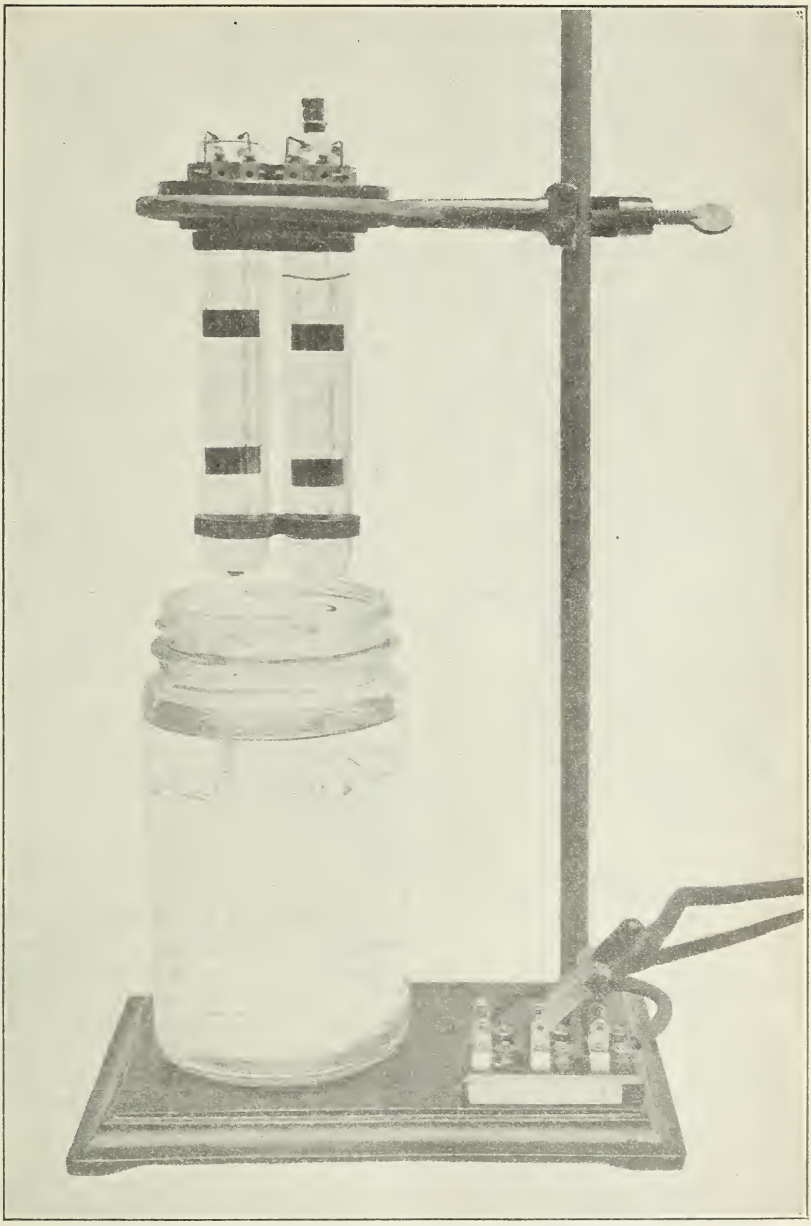

FIGURE 2.—The duplex conductivity cell and jar for containing a solution to be tested. The cells are connected to the Wheatstone bridge through a double-pole, double-throw switch by insulated leads. The closed cell containing the reference solution is on the right

In making routine conductance determinations with the duplex conductivity cell after it has been standardized, the chief precaution should be to insure temperature equilibrium between the sample and the reference solution in the closed cell. This can be done by allowing the duplex cell to remain in the sample for an hour or so before making the resistance determination. The condition of temperature equilibrium may be verified by making two or more consecutive resistance determinations, one to two minutes apart, of the solution in the closed cell. If these consecutive readings are identical, it may be assumed that the temperature is constant and therefore that equilibrium has been reached. The usual procedure, however, is to put the samples to be tested into the sample jars, set these jars together on a table with the duplex cell in one of them, and let them stand for several hours or overnight. Then the resistance for the series may be determined by transferring the duplex cell from one jar to the next and checking the resistance of the closed cell each time to verify the uniformity of temperature.

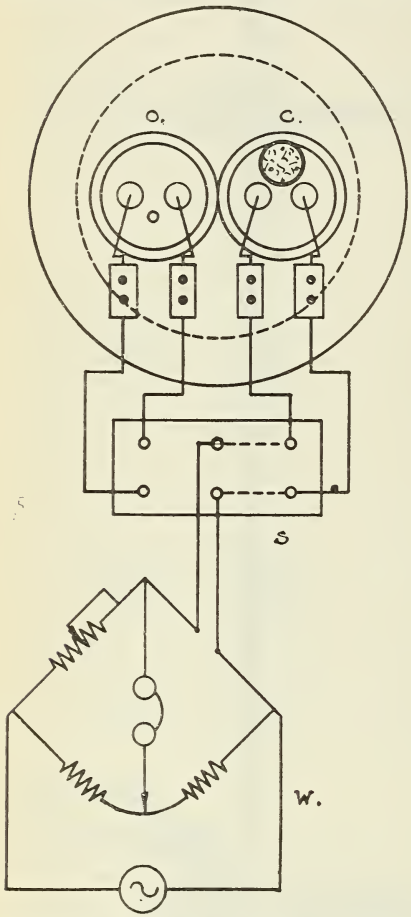

FIGURE 3.—Diagram showing the electrical connections of the duplex conductivity cell with the Wheatstone bridge: O, The open cell; C, the closed cell; S, a double-pole, double-throw switch; and W, the Wheatstone bridge

It is also advisable in the interest of precision that the sample jars should be filled to a mark made when the cell was standardized.

THE SOIL CUP

It has not been found practicable to construct glass conductivity cells for determining the specific electrical conductance of saturated soils. A cylindrical cup of hard rubber is generally used. This is equipped with two electrode studs of brass, the outer ends of which afford contacts for the leads to the Wheatstone bridge while the inner ends, set flush with the inner wall of the cup, are faced with disks of platinum. For use with saline irrigated soils it has been found desirable that the platinum-faced electrodes should have an area not greater than 0.7 cm^2 for a 50 cm^3 cup. Contact between the electrodes and the leads to the bridge is made by means of a spring yoke, the arms of which are well insulated from each other.

The soil cup is used much like any other conductivity cell. Owing to the abrasive action of the soil in filling and emptying the cup, it is necessary to clean and replatinize the electrodes more frequently than is the case with cells in which only solutions are used. The same reference solution may be used as has been suggested for use with the glass cells.

The procedure in making conductance determinations with soil is as follows: The soil sample is air dried and pulverized to pass a 2-mm sieve. It is then dried to constant weight at 110° C. One hundred grams of the dry soil are weighed into a soil can having a tight cover. Distilled water is added and the soil is stirred with a spatula until a condition of saturation is reached. In its saturated condition the soil mass should be plastic enough to flow slightly when the container is tipped. The surface should glisten as it reflects light, and the air should all be displaced. The can with its saturated soil is again weighed, and the increase in weight from the dry condition is recorded as " water required to saturate " in terms of percentage of the dry weight of the soil.

The covered soil can containing the saturated soil sample is then floated in a water bath in which also is placed the soil cup and a sample bottle containing an aliquot of the reference solution. The use of water bath facilitates attaining temperature equilibrium among the soil samples, the reference solution, and the soil cup. When temperature equilibrium has been attained the soil cup is removed from the bath, attached to the Wheatstone bridge, filled with the reference solution, and its resistance determined to obtain its cell factor for that temperature. The resistance of the reference solution multiplied by its known specific conductance at 25° C. gives a cell factor which when used subsequently in the equation $\frac{C}{R}=K$ gives the specific conductance of the saturated soil as at 25° providing, of course, the temperature of the saturated soil is in equilibrium with the reference solution. The procedure of computation used here is the same as that described for solutions on page 6.

The soil sample is transferred from the covered can to the conductivity cell with a spatula and is settled into place by gently tapping the cup on the table. The cell should be filled level full and the resistance should be read immediately to avoid temperature change. After the reading, the soil sample should be thrown out of the cell in such a manner as to cause the least abrasion of the electrode faces, and the cell should be rinsed with a stream of water rather than scraped out with the spatula.

The specific electrical conductance of a saturated soil may be designated as K_s to distinguish it from the corresponding property of a solution that is conventionally designated by the letter K. The report on a soil sample may be written, for example, as " water required to saturate," 28 per cent, "$K_s \times 10^5$ at 25° C.," 165.

INTERPRETATION OF CONDUCTANCE DETERMINATIONS

It has long been customary to report the salt content of irrigation and drainage waters in terms of gravimetric equivalents, such as

grains per gallon, parts per million, or tons per acre-foot. Consequently, there is a strong temptation to try to interpret the results of determinations of specific electrical conductance of such waters in similar terms. As a matter of fact, there can not be a precise relationship between the concentration as measured by specific electrical conductance and the concentration as determined by other analytical methods. The salt constituents of various irrigation waters occur in varying proportions to each other, and these constituents are of different ionic or combining weights. Consequently, it is not to be expected that salts of different composition would exhibit the same specific electrical conductance in solutions of identical gravimetric concentration. In fact, there may be ambiguity as to what is meant by identity of concentration in solutions. This may be illustrated by considering the two salts that are herein suggested as alternatives for use as reference solutions, viz, NaCl and KCl. In the case of these two salts, solutions that are identical as to molecular or ionic concentration, e. g., 0.01 molecular, differ not only as to specific electrical conductance but also as to gravimetric concentration. It has been stated that the specific electrical conductances at 25° C. of these salts in solutions of 0.01 molecular concentration are for NaCl 118.6×10^{-5} and for KCl 141.18×10^{-5}. With respect to gravimetric concentration these two solutions differ also. The solution of NaCl contains 585 parts per million, while that of KCl contains 745 parts per million.

It becomes evident from these comparisons that there are at least three accepted methods of stating the concentration of a salt solution and that two solutions that are of identical concentration by one of these methods may be very different when compared by the other methods. This is true not only with respect to solutions of single salts; it is equally true for solutions of mixed salts such as irrigation and drainage waters.

In view of these facts it seems preferable to report these electrometric determinations of irrigation waters in terms of reciprocal ohms. This is a definite statement of an important physical property of the solution and is quite as valid and is probably more precise and more significant than is the statement of concentration in terms of total dissolved solids as parts per million.

The greater precision of the conductance determination is due in part to the simplicity and the essential accuracy of the equipment and in part to the fact that several different methods may be, and in fact are, used for the gravimetric determination of total salts. Some analysts make that determination, after filtering the sample through paper or porcelain, by evaporating a measured aliquot to dryness and constant weight at 110° C., others dry to constant weight at 180°, and still others dry and ignite the residue at low red heat. Each of these methods gives a different result. Furthermore, it is difficult except with a highly refined technique to obtain as close agreement between the results from duplicate aliquots by any of these evaporation methods as may be obtained from duplicates by the conductance method. Some analysts have so little confidence in the accuracy and the significance of the evaporation method that they do not use it in routine work. Instead, they prefer to make quantitative determinations of the more important constituents of the salts, such as the carbonates, bicarbonates, chlorides, and sulphates, and

sometimes the nitrates, calcium, and magnesium; and from these determinations they compute the concentration of the solution in terms of milligram equivalents or as parts per million. By this method also the agreement of results between duplicate aliquots is seldom as close as those of the conductance method.

With respect to the significance of the results obtained by the electrometric as compared with the evaporation method, it is believed that the electrometric method has the advantage. There are two reasons for this belief. One is based on the occurrence in irrigation and drainage waters of measurable quantities of nonelectrolytes, such as silica and dissolved organic matter that are relatively inert with respect to their effects on plants. These contribute to the total salt content as determined by the evaporation method, but do not affect the electrometric determination. The other reason relates to the differences in the atomic or ionic weights of the salt constituents. For example, the chloride ion weighs 35.5, while the corresponding sulphate ion weighs 48 (96÷2). A solution of NaCl having a concentration of 0.01 normal, or 585 parts per million, has at 25° C. a specific electrical conductance of 118.6×10^{5} reciprocal ohms.[6] A solution of Na_2SO_4 having the same ionic concentration (0.01 normal) has a gravimetric concentration of 710 parts per million and a specific electrical conductance, at 25°, of 112.39×10^{-5}. There is abundant evidence both from field observations and laboratory work to support the view that of the two salts at equal ionic concentration, Na_2SO_4 is less injurious to crop plants than NaCl. If two such solutions are compared with respect to specific electrical conductance and gravimetric concentration, it will be seen that the sulphate solution is lower in conductance as it is in toxicity, while in gravimetric concentration it is higher.[7]

These facts appear to support the view that as a means of measuring the concentration of salts in irrigation water in relation to the effect of such concentration on crop plants, the electrometric method is better than the evaporation method.

There are circumstances in which it is desirable to compute approximately the gravimetric equivalents of conductance determinations, as in case of an irrigation or drainage stream of which the discharge is recorded and it is desired to record also the tonnage of salt carried. In such a situation the indicated procedure is to take occasional samples for chemical analysis, including a gravimetric determination of the total dissolved solids and the specific electrical conductance. The ratio of the electrical to the gravimetric determinations on these occasional samples may be used as a conversion factor for computing the gravimetric equivalents of the intermediate or more frequent conductance determinations on that stream.

With experience in the use of conductance measurements, standards of comparison are adopted that are as useful as those derived from gravimetric determinations. It is not more difficult to remember the figure 200 than the figure 1,500 if one finds by experience that water of that concentration is the limit of safety for irrigation use, the figure 200 being in the conductance scale and 1,500 being in the gravimetric scale.

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[6] See footnote 3.

[7] It is not intended to imply that there is any general or basic relationship between conductance and toxicity for all the salt constituents found in irrigation water.

It is not proposed here that the electrometric determination of the concentration of salts in irrigation waters or in soil solutions should be used instead of chemical analysis. It is only by means of chemical analysis that information may be obtained as to the composition of the salts in such a solution. But there are many circumstances in which interest centers on the question of the relative concentration of the solutions from time to time or from place to place in the same area. In such circumstances the electrometric method should prove useful because of its simplicity and high accuracy.

The relationship between concentrations as measured by the three methods may be illustrated by giving the results reported on a series of samples of irrigation and drainage waters. The three methods are: (1) Specific electrical conductance, (2) analyses reported in terms of milligram equivalents, and (3) the gravimetric determination of the total dissolved solids. For comparison also the list includes the three pure salts already discussed to illustrate these relationships of concentration. (Table 1.)

TABLE 1.—*Concentrations of water solutions of pure and mixed salts as expressed by specific electrical conductance, by milligram equivalents (ionic concentration), and by gravimetric proportions*

Laboratory No.	Description	$K \times 10^5$ at 25° C.	Milligram equivalents, sum of anions	Gravimetric determination as parts per million
	Potassium chloride, 0.01 normal	141. 18	10. 00	745
	Sodium chloride, 0.01 normal	118. 6	10. 00	585
	Sodium sulphate, 0.01 normal	112. 39	10. 00	710
4204	Sacramento River at Tisdale, Calif., May 16, 1931	24	2. 16	143
4205	Sutter Basin drain at Karnak, Calif., May 16, 1931	248	23. 40	1, 690
4339	Santa Clara River at Santa Paula, Calif., June 2, 1931	154	18. 12	1, 235
4348	Piru Creek at Piru, Calif., June 16, 1931	153	17. 74	1, 202
4347	Sespe Creek at Fillmore, Calif., June 16, 1931	91	9. 63	615
4319	Los Angeles Aqueduct at San Fernando, Calif., June 9, 1931.	44	4. 27	287
4333	Colorado River at Yuma, Ariz., June 11, 1931	65	6. 74	450
3710	Colorado River at Yuma, Ariz., Jan. 22, 1931	196	21. 51	1, 415
4318	Yuma Valley drain, Yuma, Ariz., June 7, 1931	188	18. 79	1, 166
4350	Alamo River (drain), Imperial Valley, June 11, 1931	116	11. 01	723
4349	New River (drain), Imperial Valley, June 11, 1931	165	15. 78	1, 008
4353	Holtville drain, Imperial Valley, June 11, 1931	502	51. 72	3, 215
4354	Trifolium drain, Imperial Valley, June 11, 1931	1, 523	167. 96	10, 550
4228	Gila River, Florence, Ariz., May 29, 1931	135	13. 90	834
4229	Salt River, Stewart Mountain Dam, Ariz., May 29, 1931.	105	9. 83	602

It will be observed that these samples of irrigation and drainage waters range in concentration as expressed by specific electrical conductance in reciprocal ohms ($K \times 10^5$ at 25° C.) from 24 to 1,523. From field observations it appears justifiable to conclude that in this scale 200 represents approximately the critical concentration. In other words, irrigation waters having a specific electrical conductance at 25° of less than 200×10^{-5} reciprocal ohms are in general not injurious to crop plants, while the use of waters of higher concentration is likely to result in crop injury. It will be understood that there can not be an inflexible standard as to the critical concentration of irrigation water for three reasons: (1) Crop plants do not all have the same degree of salt tolerance, (2) different irrigation supplies may differ in the relative proportions of their salt constituents, and (3) the ratio of the concentration of the irrigation water to that of the resulting soil solution is conditioned by such factors as the

character of the soil, the local drainage conditions, and the quantity of water applied. In very general terms it may be said that where the conductance value ranges slightly above 100, the water contains approximately 1 ton of salts per acre-foot.

CONDUCTANCE OF SATURATED SOIL

In describing the procedure for using the soil cup for conductance determinations it was suggested that the soil sample should be saturated with distilled water and that the result of the determination be expressed as "$K_s \times 10^5$ at 25° C." This designation implies the specific electrical conductance of the saturated soil as reciprocal ohms $\times 10^5$ at 25°. Here, as with water solutions, it is proposed to report the direct result of an observation rather than to attempt to convert the electrometric result into some corresponding gravimetric scale, such as the percentage of soluble salts based on the dry weight of the soil. It is believed that this method of procedure gives results that are more accurate and more significant than may be obtained either by expressing resistance measurements as percentages of salt in the soil or by digesting a sample of soil in distilled water and then analyzing an aliquot of the solution thus obtained.

The difficulties that are encountered in attempting to convert electrometric determinations on soil into a scale of salt percentages are even greater than those enumerated for comparisons of solution concentrations. In either case the measurement involves the resistance offered by a solution between two electrodes. In one case the conductivity cell is filled with the solution, while in the other the cell contains a mass of soil with the solution occupying the spaces between the soil particles. It is assumed that the soil itself is essentially a nonconductor. In a saturated soil the proportion of solution to solid soil varies with the texture of the soil. A soil composed of small particles, such as silt or clay, holds more water than a sandy soil. This involves two significant results. One is that a statement of the quantity of water required to saturate a weighed quantity of dry soil is a good way of indicating the texture of the soil. The other is that in a given volume of saturated soil, e. g., the 50 cm^3 in a soil cup, the actual quantity of solution between the electrodes varies with the saturation percentage of the soil. Therefore, if two soils, one coarse and one fine in texture, contained the same quantities of the same salt, based on the dry weight of the soil, the solution between the electrodes would be relatively less in volume but more concentrated with the coarse soil than with the other. To some extent the greater resistance of the lesser volume would be offset by the lesser resistance of the higher concentration, but the extent of this compensating effect is not known. The point of major importance is that the determination of the percentage of water required to saturate a sample of soil is a more satisfactory indication of its texture than such descriptive terms as sand, fine sand, loam, or clay. And some indication of soil texture is helpful to an understanding of soil conditions in relation to salinity. Incidentally it has been observed that the percentage of water required to saturate a soil is approximately twice the percentage of "moisture equivalent" for other than very sandy soils.

It is sometimes suggested that in view of the uncertainties as to the effects on electrical resistance of the presence of soil between the

electrodes, and in view of the varying proportions of solution to soil on account of soil texture, it might be more satisfactory to extract an aliquot of the soil solution for a conductance determination rather than to measure the conductance of the saturated soil. Both methods have been used, and while each gives useful results, it is believed that the conductance of the saturated soil is more dependable as an indication of plant reactions than is the conductance of the extracted solution. This belief is based partly on field observations and laboratory experiments, too extensive to be discussed here, and partly on a comparison of the two methods on a series of soil samples representing known field condition.

It has been found, for example, that some soils contain relatively high proportions of salts of low solubility, such as $Ca(HCO_3)_2$ and $CaSO_4$. The limit of solubility of both of these salts is well below the limit of tolerance of most crop plants. In other words, most crop plants are not injured if the soil solution is saturated with respect to these two salts. On the other hand, the limit of solubility of such salts as NaCl and Na_2SO_4 is well above the limit of tolerance of crop plants. The chief point of interest, from an agronomic standpoint, is the concentration of the soil solution actually in contact with the plant roots. If all of the soluble salts in the soil were of high solubility, then the concentration of the solution would be inversely proportional to the water content of the soil, and one might compute the concentration of the soil solution as at field capacity from the determined concentration of a solution obtained by digesting the soil with a definite proportion of water. But since varying and unknown proportions of the salts in the soil are of low solubility, the digestion of a soil sample with water to obtain a free solution for a conductance determination may bring into solution a substantial but unknown quantity of salts of low solubility that would not be in solution if the water content were at or below the field capacity. Consequently, it is believed that there is greater likelihood of approximating true soil-solution conditions if the conductance measurement is made on a sample of saturated soil than if it is made on a free solution extracted from the soil after digestion. In routine soil-digestion work it is customary to use more water than soil. Some analysts use 2 parts, by weight, of water to 1 of soil; others use 5 parts to 1, and still others use 10 parts to 1. In saturated soils as used in conductance determinations the proportion of water to soil may be as low as 0.2 to 1 and is seldom higher than 0.6 to 1. Thus it will be seen that the solution obtained by merely saturating the soil is likely to be more comparable to the soil solution as at field capacity than is the solution obtained by digestion with a water-soil ratio of 2 to 1 or 5 to 1.

It is not practicable to measure accurately the resistance of the solution suspended in the soil unless the soil is saturated. Consequently, the moisture content at the saturation point appears to be the nearest approximation to the moisture content at field capacity that it is possible to use in conductance determinations. Attempts have been made to develop a method of obtaining an aliquot of the natural soil solution by displacing the solution from a sample of moist but unsaturated soil. It is possible to displace the suspended solution from a soil by the use of any one of several different liquids. However, it has not been shown that the solution obtained by dis-

placement is truly representative of the solution originally suspended in the soil. The occasion for doubt as to its representative character lies in the fact that as the displacing liquid penetrates the upper part of a column of soil the displaced solution passes downward, increasing the moisture content of the lower section of the column which must become saturated before any free solution may be obtained from it.

In view of all these circumstances it is concluded that the method here proposed, of wetting the soil sample to the saturation point and then measuring the electrical resistance of the solution thus obtained in the soil, is the most practicable one now available for routine use in determining the salinity of irrigated soil. The most obvious disadvantage of this method is that the conductance results obtained by its use are not easily to be compared with results from other methods of soil analysis. The most dependable basis of interpreting the conductance determinations is by reference to the observed reactions of crop plants growing on soils that are tested by this method.

An extended series of tests of irrigated soils has shown that when the specific electrical conductance of the saturated soil in reciprocal ohms at 25° C. ($K_s \times 10^5$ at 25°) is less than 200 the salinity of the soil solution is below the limit of tolerance of most crop plants. In the more productive irrigated soils where there is free subsoil drainage and the irrigation is adequate to keep the root zone leached, the conductance figures range below 100, often as low as 40 or 50. On the other hand, when conditions of crop growth indicate soil salinity, the conductance figures range well above 200, reaching 500 or higher in soils that are too saline to support crop growth. It will be understood, of course, that these figures refer to soil conditions in the root zone. It is well known that the distribution of salinity in the soil profile is highly variable. Salts may be accumulated in the surface soil above the root zone, or the concentration may be much higher in one section of the root zone than in another.

As a way of illustrating the relationship between the conditions of soil salinity and the conductances of saturated soils, the reports on a series of samples are given in Table 2.

TABLE 2.—*Specific electrical conductance of samples of saturated soil at 25° C., expressed as reciprocal ohms $\times 10^5$ and the texture of the soil as indicated by the percentage of water required to saturate it compared with conditions of productivity*

Location and conditions	Profile section	Water to saturate	$K_s \times 10^5$ at 25° C.
	Feet	*Per cent*	
Yuma Valley, good cotton	1	46	94
	2	33	53
	3	38	62
	4	35	47
Imperial Valley, good grapefruit	1	41	85
	2–3	42	109
	4	45	182
Imperial Valley, injured grapefruit	1	74	540
	2–3	66	429
	4	63	429
San Joaquin Valley, good orchard	0–3	33	54
San Joaquin, Valley, injured orchard	0–3	37	462
San Fernando Valley, good lemons	0–0.5	30	237
	0.5–3	28	48

It will be observed that the conductance of well-drained soil in the Yuma Valley ranges well below 100 even though the irrigation water, which is from the Colorado River, carries rather more than 1 ton of dissolved salts per acre-foot as an annual average and the soil represented by these samples has been irrigated with such water for 20 years.

The two sets of samples from the Imperial Valley represent soils that have been irrigated for many years with Colorado River water. The samples in the first group, from land producing good grapefruit, show higher conductances than the Yuma soils, particularly in the deeper section of the root zone. The soil also has a finer texture, as is indicated by its higher saturation percentage. The samples in the second group represent a soil of much finer texture with a higher saturation percentage and much higher conductances throughout the 4-foot section. The grapefruit trees growing on this soil showed clearly the injurious effects of the high concentration of salts in the soil solution.

The samples from a deciduous-fruit orchard in the San Joaquin Valley were selected to show the conductances at two locations in the same orchard. At one location the tree growth was normal, while at the other, a bare spot in the orchard, there were no living trees, although a second planting of trees had been made. The samples from the San Fernando Valley were both taken from the same location in a lemon grove where growth conditions were good. The sample of surface soil showed a high conductance, while the sample from the root zone showed a low conductance. This grove was irrigated by furrows, and although the irrigation water contains very little salt, it is evident that by this method of irrigation there is a tendency for salt to accumulate in the soil of the ridges between the irrigation furrows.

The list of soil samples included in Table 2 indicates fairly well the range of conductances and of saturation percentages that may be expected in irrigated soils. No attempt is made to show the salinity of these samples such as might be determined or other methods of analysis. It is believed that the method of electrical-conductance determination, whether used with free solutions such as irrigation or drainage waters or with soil samples, gives results that may be interpreted usefully without reference to standards of comparison based on other methods of determining salinity. Conductance determinations have proved to be useful also in connection with routine laboratory analyses of water samples, in that they serve as an independent check on the results obtained by analytical methods.

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